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Model simulations of continuous ion injection into EBIS trap with slanted electrostatic mirror[1]

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The efficiency of trapping ions in an EBIS is of primary importance for many applications requiring operations with externally produced ions: RIA breeders, ion sources, traps. At the present time, the most popular method of ion injection is pulsed injection, when short bunches of ions get trapped in a longitudinal trap while traversing the trap region. Continuous trapping is a challenge for EBIS devices because mechanisms which reduce the longitudinal ion energy per charge in a trap (cooling with residual gas, energy exchange with other ions, ionization) are not very effective, and accumulation of ions is slow. A possible approach to increase trapping efficiency is to slant the mirror at the end of the trap which is opposite to the injection end. A slanted mirror will convert longitudinal motion of ions into transverse motion, and, by reducing their longitudinal velocity, prevent these ions from escaping the trap on their way out. The trade off for the increased trapping efficiency this way is an increase in the initial transverse energy of the accumulated ions. The slanted mirror can be realized if the ends of two adjacent electrodes- drift tubes – which act as an electrostatic mirror, are machined to produce a slanted gap, rather than an upright one. Applying different voltages to these electrodes

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will produce a slanted mirror. The results are presented of 2D and 3D computer simulations of ion injection into a simplified model of EBIS with slanted mirror.

1. Introduction

The most popular method of injection the externally produced ions into EBIS trap is a fast potential trapping. With one axial potential barrier on the side opposite the injection end the ions from an external source are traversing the trap region and escape in the direction they came from. At a time when the trap region is filled with traversing ions the second barrier on the side of injection is raised and ions between two axial barriers are trapped. In the radial direction these ions are confined by the electric field of the electron beam space charge. Since the maximum number of trapped ions with this method is limited to the number of ions traversing the trap region, the injection of light ions in a multiampere electron beam becomes problematic. On the other hand, slow ion injection is not limited to the traversing time and utilizes mechanisms, which reduce the ion longitudinal energy per charge during their traversing the trap region (ionization, energy loss in ion-ion and ion-molecule interactions). Since the probabilities of these processes during the traversing time are small, the injection of sufficient number of ions can take time comparable or longer than the necessary ionization time. The charge state spectrum in this case will have a low-charge state tail typical for continuous injection from gas in a trap region.

2. Concept of ion injection with slanted electrostatic mirror

Potential trap of EBIS is created by the electron beam space charge providing radial confinement of positive ions and by two axial potential barriers on both sides of the ion trap to prevent ions from leaving the trap axially. With continuous external ion injection, the axial barrier on the injection side of the trap (first barrier) has to be lower, so that ions which passed this barrier will be reflected from the second one (second barrier) on the opposite side of the trap.

To prevent ions which are traversing the trap region from leaving the trap, the axial component of kinetic energy per charge needs to be reduced before they reach the second barrier. This can be done by transferring part of the longitudinal energy component into transverse component (radial and azimuthal) when the ion is reflected by an electric field which is not parallel to the axis of ion motion. The simplest configuration of electrodes generating such inclined electric field would be two adjacent cylindrical electrodes with facing parallel edges cut at an angle different from 90^o with respect to the axis. Some ions (with most of energy in a longitudinal direction) reflected from the slanted electrostatic mirror will lose some of their longitudinal component of energy and will be trapped. Their transverse energy will increase, but as long as the radial energy gain does not exceed the potential difference between the point of reflection and the wall, this ion will not hit the wall and will stay in a trap region. The other ions (with a high share of transverse component in total energy) will increase their longitudinal component of energy and will leave the trap region. Whether the ion will be trapped or accelerated and reflected back will depend on the angle of the ion's velocity with the reflecting equipotential surface. Obviously, ions near the axis are better trapped than the peripheral ions. Based on this simplified model, one would expect the slanted mirror to be more effective in a region of the trap with the largest average ratio of longitudinal to transverse energies.

3. 2D simulations

For both 2D and 3D simulations, the electron current was i_{el} 5.0 A, electron energy E_{el}=25.0 keV, electron beam radius r_{el}=3.0 mm, inner radius of drift tubes r_t=10.0 mm, magnetic field in the trap region B=0.3 T. The injected monoenergetic ion beam had radius r_{ion}=4.0 mm with zero emittance, zero divergence and zero current.
2D simulations have been done with program TRAK [[1]]. Because of limitations of the 2D program with cylindrical symmetry the model of slanted mirror was substituted with model of conical mirror. The number of electrons was 100 and number of ions – 100.
The 2D model with potential and magnetic field distributions is presented in Fig.1.
The electron beam transmission through this structure is presented in Fig. 2. With magnetic field of 0.3 T the effect of slanted mirror on the electron beam transmission is relatively small. Without axial barriers the ions injected into electron beam are passing through the trap region without reflection on the second barrier, and none of them get trapped. With both axial barriers in place the slanted mirror becomes active and ion

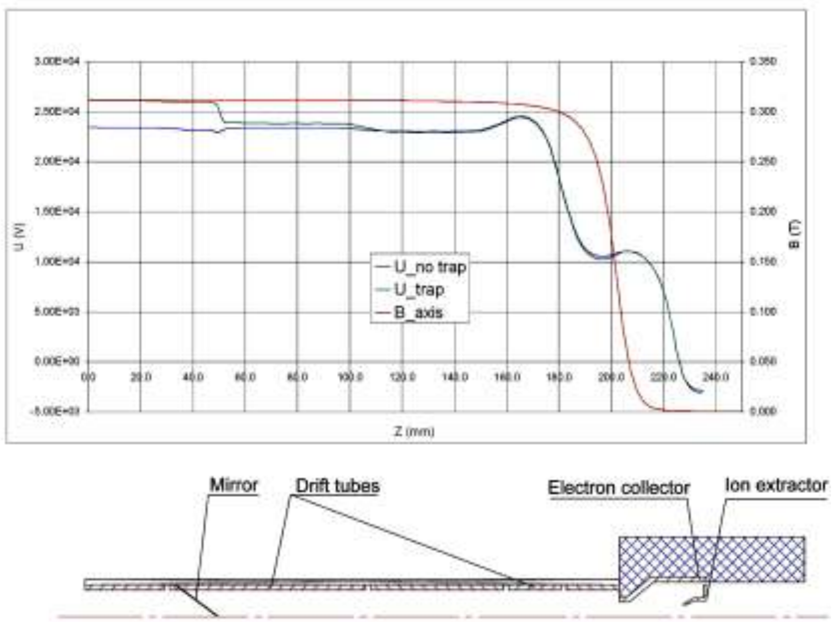

Fig. 1. 2D model with axial potential and magnetic field distributions

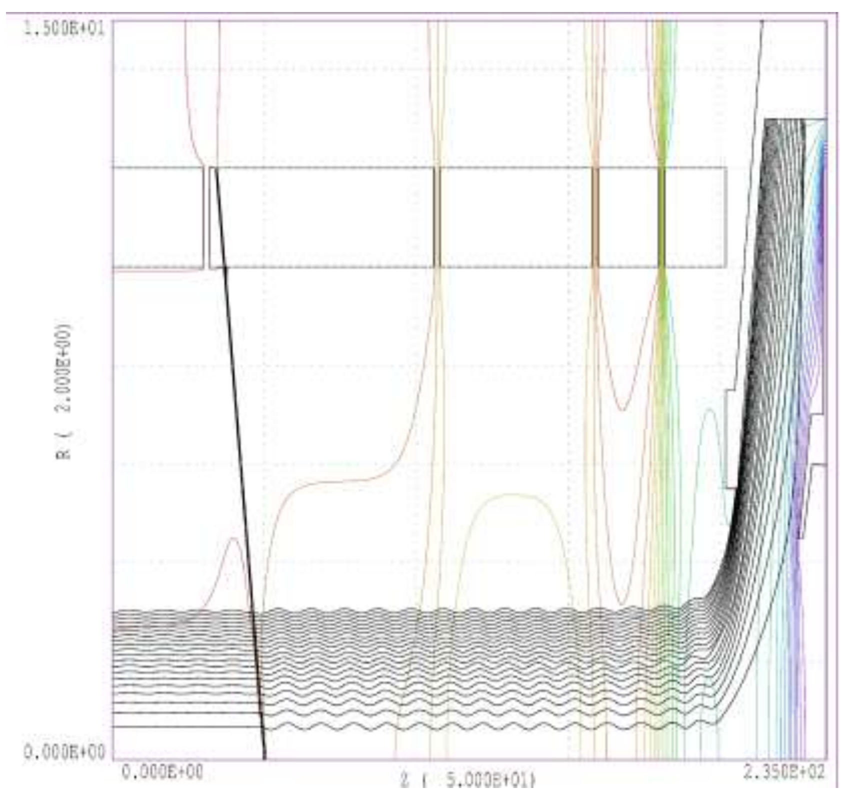

Fig. 2. Simulated electron beam transmission in 2D model of ion trap with slanted mirror

energy transfer and therefore ion accumulation takes place. The simulated ion trajectories with trapping potential distribution on the drift tubes are presented in Fig. 3.

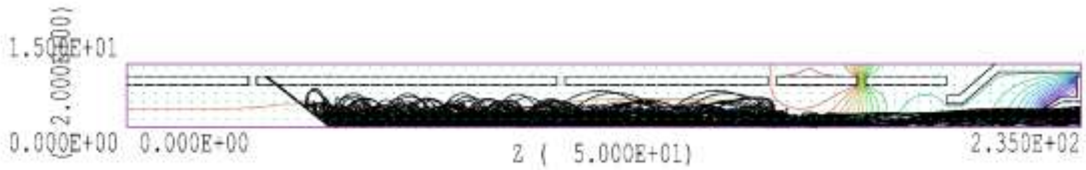

Fig. 3. Simulated ion trajectories in a trap with active slanted mirror 45 degrees.

One can see that in a process of ion accumulation the effective diameter of ion system in a trap increases. The trajectory of a single trapped ion oscillating between two potential barriers is presented in Fig. 4.

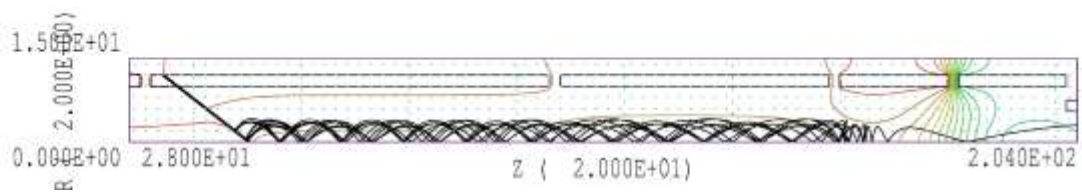

Fig. 4. Simulated trajectory of a single ion trapped between two barriers

This ion makes nine reflections in a trap, did not come out of the trap and did not hit the wall.

The results of 2D simulations for a slanted mirror angle of 45^0 are presented in Fig. 5.

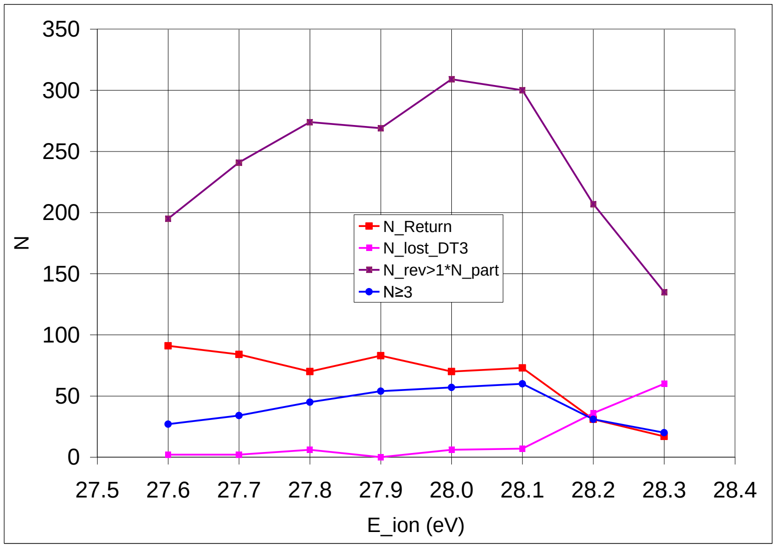

Fig. 5. Ion trapping statistics for 2D model of slanted mirror with angle 45 degrees. N_Return - number of ions returned to the origin, N_lost_DT3 - number of ions bounced of the mirror and lost on a wall of the mirror electrode on the trap side, N_rev>1*N_part - sum of the products of number of reflections times number of ions, which made these reflections, N>3 - number of ions experienced 3 or more reflections.

The maximum number of ions with more than 3 reflections reaches 60 out of 100. With increasing ion energy, the number of ions returning back decreases because of trapping, loss on drift tubes, or penetrating the second barrier and escaping in the direction of initial motion. The upper curve shows a gain in number of ions in a trap because of trapping ($\Sigma[N_i \cdot i]$, N_i – number of ions with i reflections). Considering that number of ions entering the trap region is usually less than 100 because of reflection from the first barrier this gain is seen as substantial. The width of curves ($N \geq 3$) and (N_rev>1*N_part) is approximately 500 eV, which corresponds to the radial potential well within electron beam area populated with ions. From Fig. 6 one can see that accumulation of ions in 2D model for the existing conditions in a trap has maximum at 45^0.

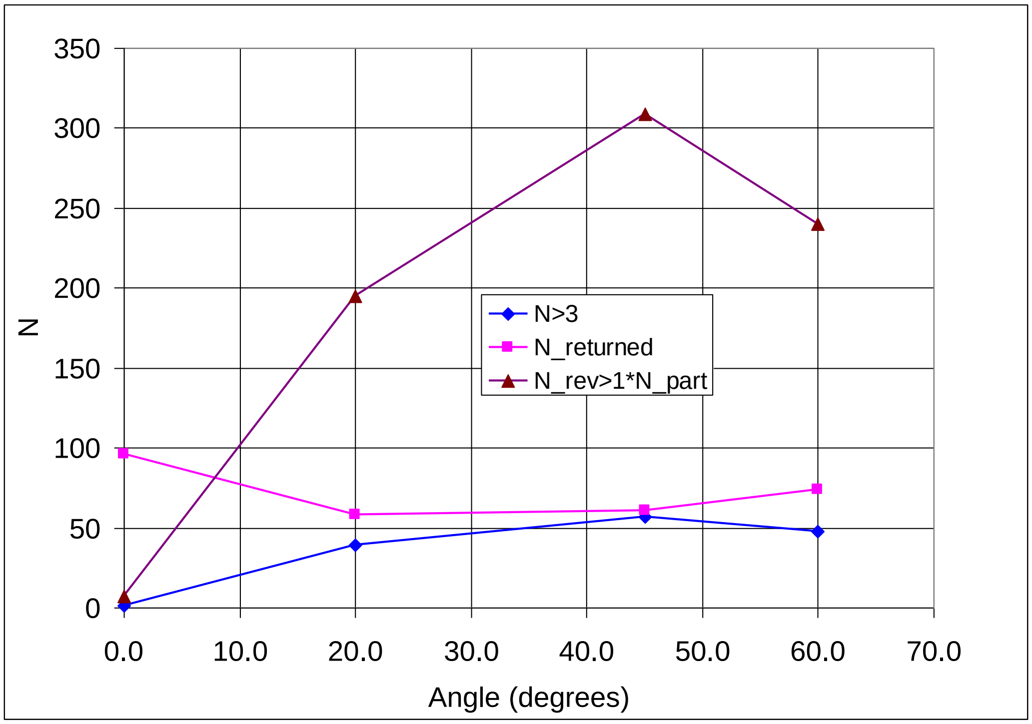

Fig. 6. Dependence of ion trapping efficiency on the angle between mirror cut plane and axis for a fixed voltage between mirror electrodes 2.4 kV (2D model).

4. 3D simulations

For 3D simulation was used program KOBRA3-INP [2]. A model for 3D simulations is presented in Fig. 7. The picture of electrostatic field map with electron beam space charge in this 3D model is presented in Fig. 8.

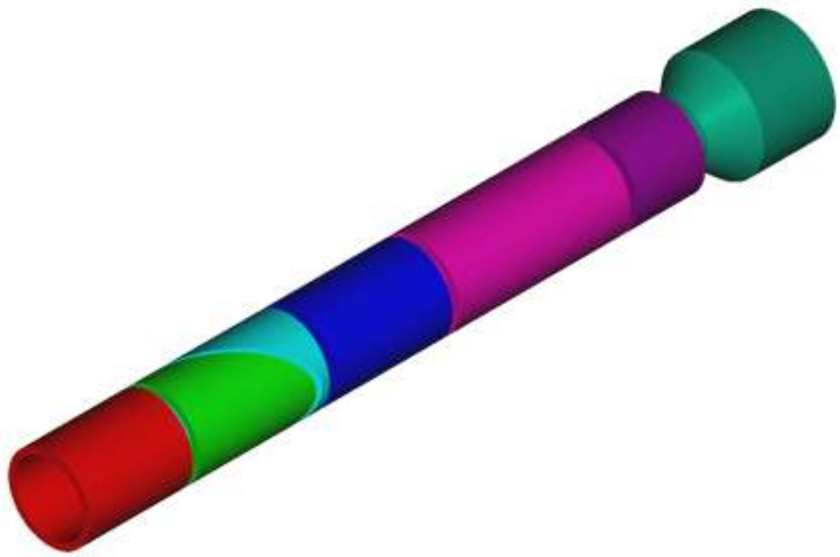

Fig. 7. 3D model of the ion trap with slanted mirror.

The results of simulations for different slanted angles of the mirror are presented in Fig. 9.

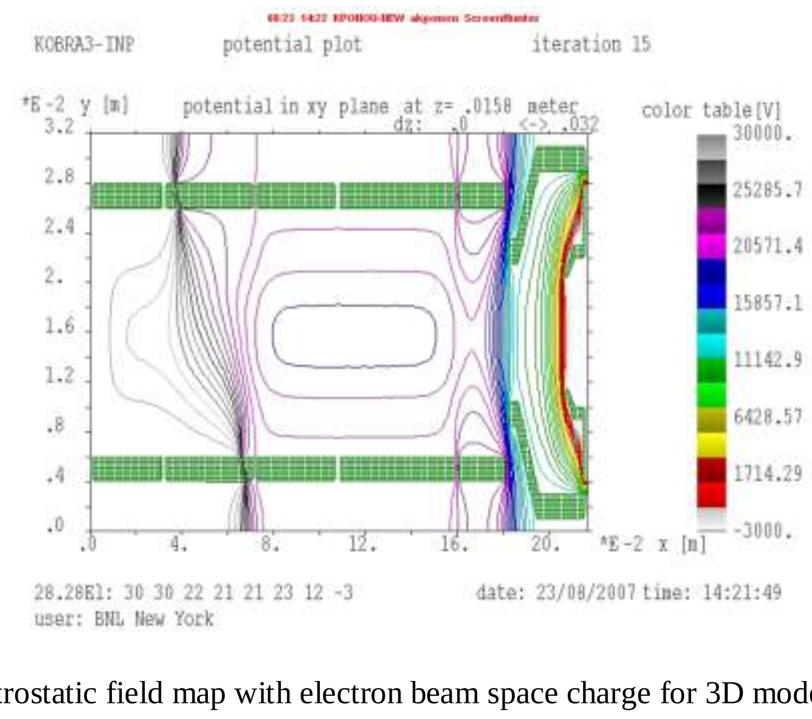

Fig. 8. Electrostatic field map with electron beam space charge for 3D model of the ion trap with slanted mirror (mirror angle 20 degrees).

Since the voltage between mirror electrodes determines the position and shape of the reflecting equipotential an attempt was made to simulate the dependence of trapping efficiency the voltage difference between adjacent mirror electrodes.

The results of 3D simulations for different mirror angles are presented in Fig. 9.

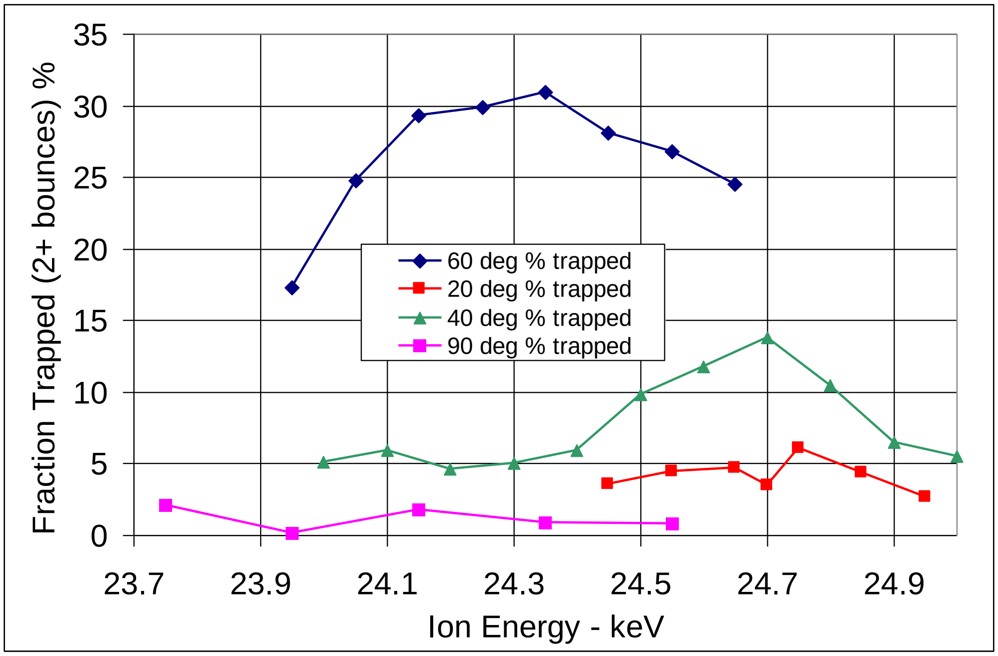

Fig. 9. Dependence of number of trapped ions on the ion energy for different mirror angles (3D model). The voltage difference between mirror electrodes was fixed at 3.0 kV.

As one can see from Fig. 10 this voltage has strong effect on the efficiency possibly because of effectively changing the angle of the reflecting equipotential in the ion reflection region. As an alternative method of controlling this angle it is possible to build a mirror not of 2 electrodes but of 3 or more with additional wedge-shaped electrodes in a gap between side electrodes (Fig. 11).

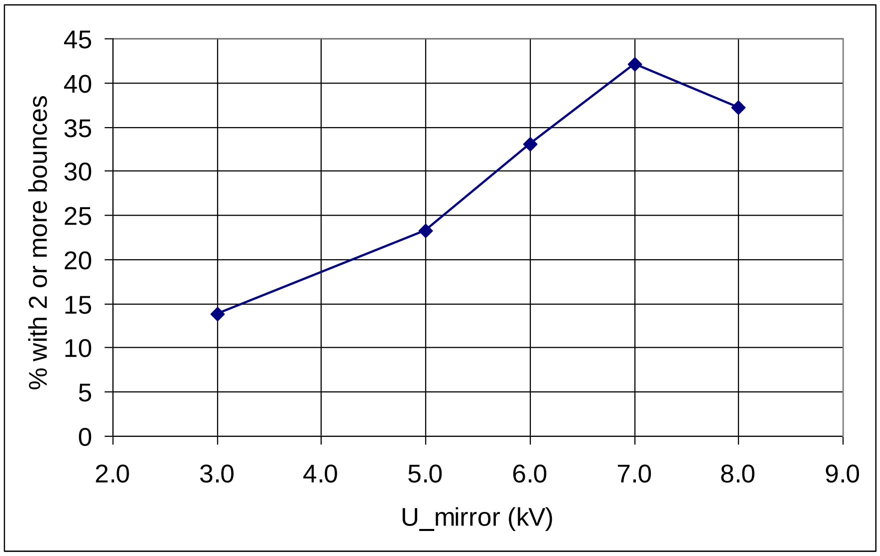

Fig. 10. Dependence of trapping efficiency on the voltage difference between mirror electrodes for fixed mirror angle 20 degrees.

Such geometry of electrodes allows varying the mirror angle in a wider range than just by changing the voltage between mirror electrodes.

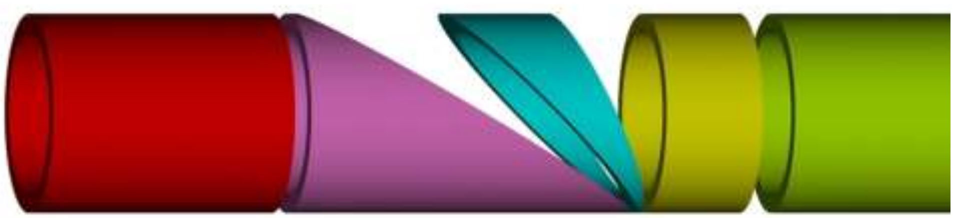

Fig. 11. 3D model of slanted mirror with tunable angle using an additional wedge-shaped electrode.

5. Conclusion

With all quantitative differences in simulations with 2D and 3D programs it was demonstrated that, at certain conditions, the continuous trapping of ions traversing the EBIS trap by transferring part of longitudinal energy into transverse with slanted electrostatic mirror is possible, and the trapping efficiency exceeds 30%. The efficiency of ion trapping depends on the angle of the mirror with beam axis, probably having maximum in a range $45^0 – 60^0$. Adjustment of this angle seems to be useful for the required equilibrium.

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[1] http://www.fieldp.com

[2] http://www.inp-dme.com/inp/3s_1.html